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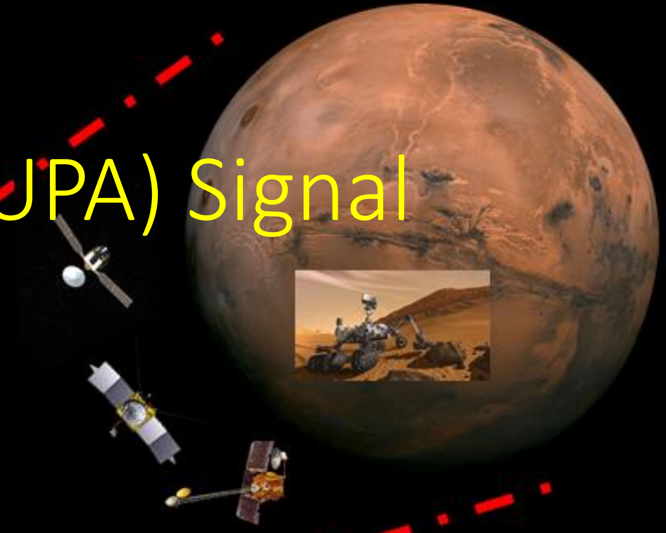
Multiple Uplinks Per Antenna (MUPA) Signal Acquisition Schemes



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Scope and Background

- Traditionally deep-space operations made use of a single ground antenna to communicate with a single flight asset
- More recently the technique of Multiple Spacecraft Per Antenna (MSPA) was developed to allow a single ground antenna to receive downlink signals from multiple spacecraft
  - Such as the case with multiple spacecraft in orbit around Mars within the half-power beamwidth of a 34-m antenna at 8.4 GHz (X-band)
- It is desired to extend this technique to the uplink using a single ground antenna to multiple spacecraft within the same beam
  - Such a technique could be applicable to
    - Numerous small SAT constellations being considered for future missions
    - Future spacecraft at Venus, Mars, or elsewhere in the solar system

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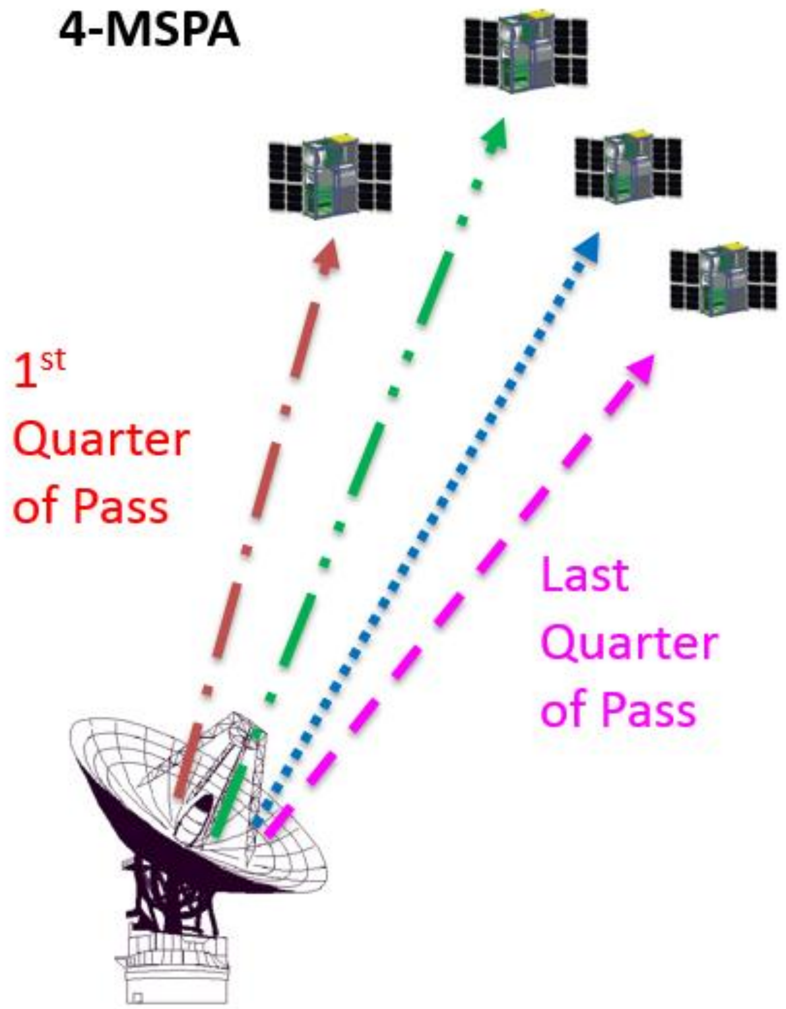
Uplink to Multiple Spacecraft from a Single Ground Antenna



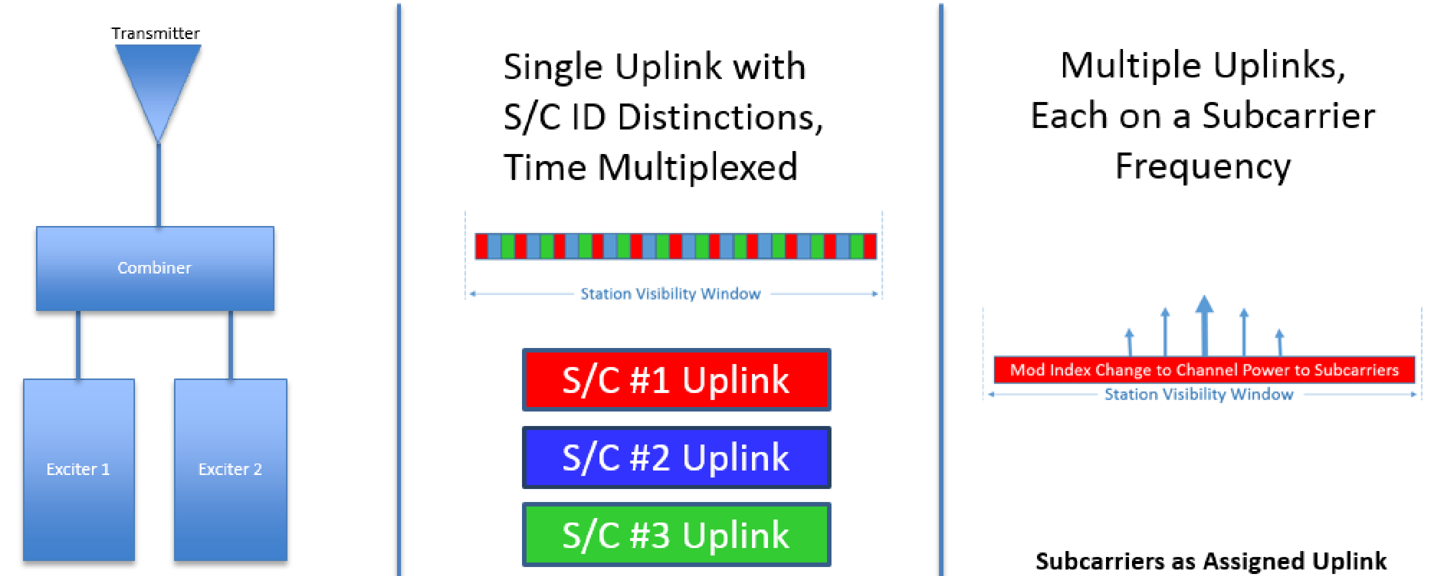
- Serial uplink swapping allows each spacecraft to share a portion of the pass for uplink while 4-MSPA is occurring on the downlink.
  - Allows each spacecraft to get in some 2-way Doppler and ranging, as well as commanding.
  - Up to 30 minutes required for the handover to each successive spacecraft.
- More efficient use of the antenna could occur if simultaneous Multiple Uplinks Per Antenna (MUPA) is possible.

Uplink to Multiple Spacecraft from a Single Ground Aperture, cont'd

- Simultaneous uplink to multiple spacecraft
  - Multiple Exciters (multiple uplink frequencies) using a single transmitter
  - Single uplink frequency with commanding differentiated by a unique identification code for each member spacecraft (recommended)
  - Multiple subcarriers modulated on a single carrier – data from each subcarrier intended for one of the multiple spacecraft

In-Beam, Simultaneous, Multi-Spacecraft Uplink

3 Techniques Under Investigation



Multiple Exciters
(Requires 80 kW tubes to reduce intermodulation effects)

Single Frequency
(Requires some accommodation on spacecraft and coordination with other users)

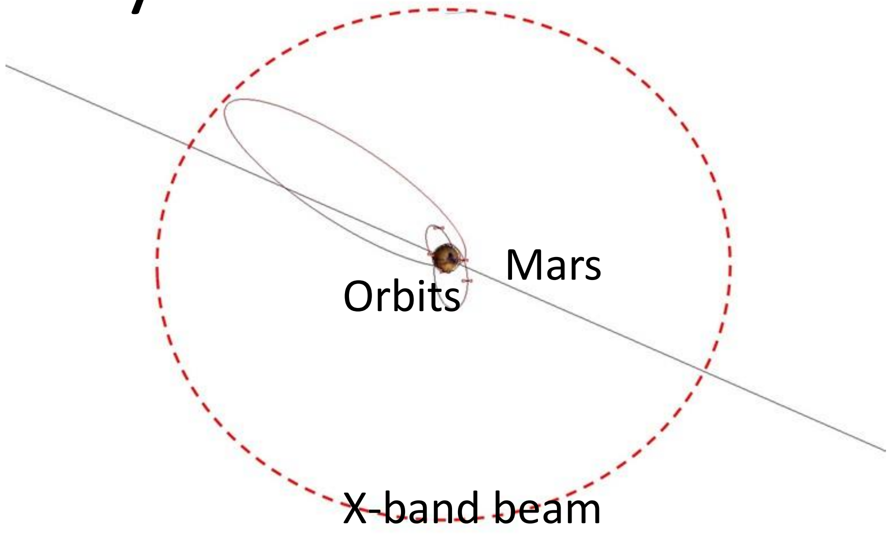
Subcarriers as Assigned Uplink Frequencies
(Requires coordinated spectrum assignments; multiple schemes with varying power and bandwidth efficiencies)

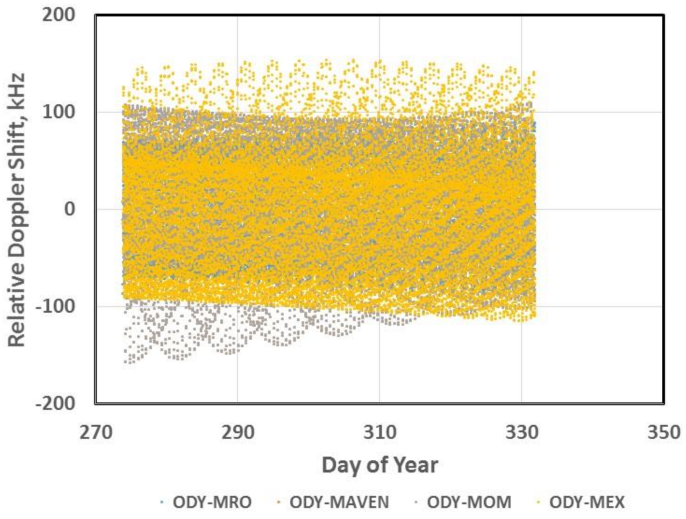
MUPA – Single uplink frequency with commanding differentiated by SC ID code

- Easy to implement and lower cost
- Minor SW changes on ground to handle 2-way Doppler and Range
- Would require variable turn-around ratios on spacecraft radio
- Large Doppler shifts are problematic for sweeping and achieving lock
    - But manageable using SDRs and on-board digital signal processing
- We baselined a hypothetical constellation of a set of orbiters around Mars using existing spacecraft orbit trajectories

MUPA – Geometry

- Examined case of 5 spacecraft currently in orbit around Mars making use of their trajectories to infer relative Doppler offsets and rates
    - Based on ~ 2 month period from Sep. 30 to Nov. 27, 2016
- Relative Doppler shift gets as high as 163 kHz
- These shifts can get higher or lower depending on time interval in question
- In actuality, one would evaluate the relative shifts over shorter time periods





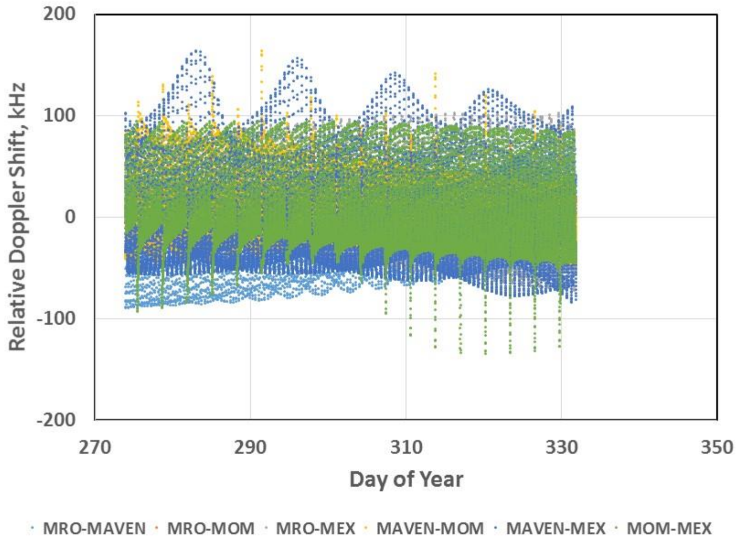
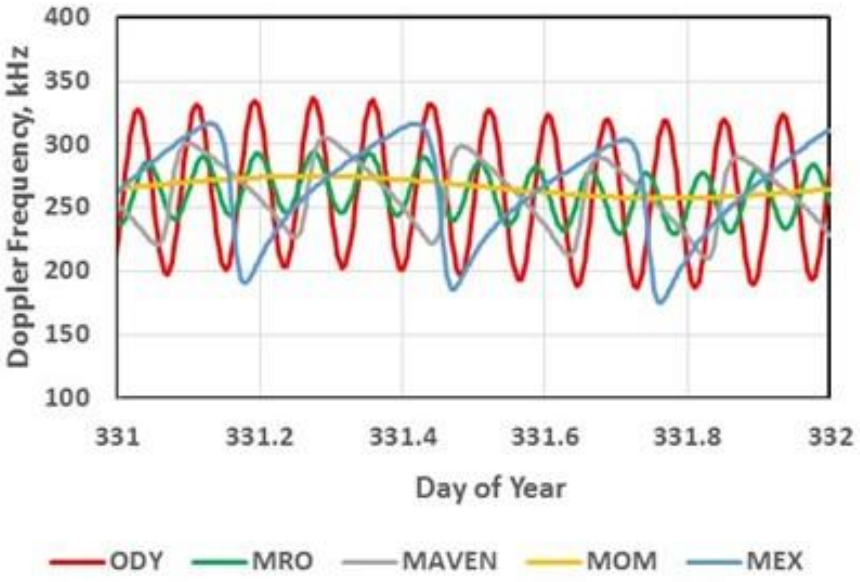
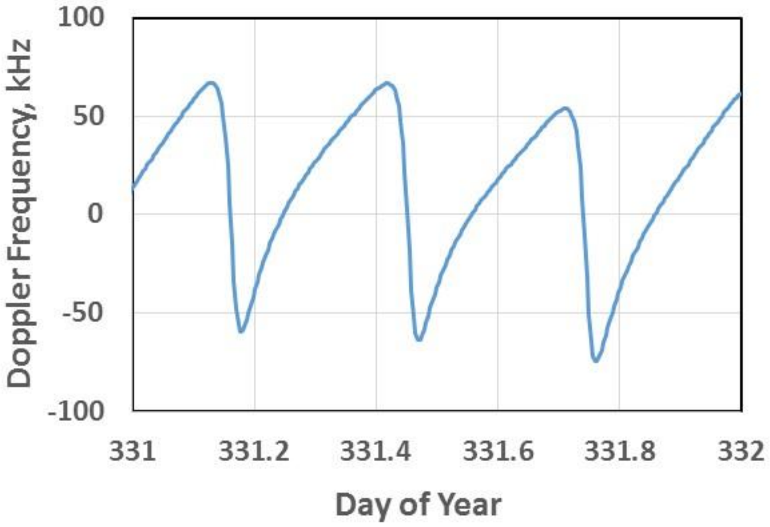


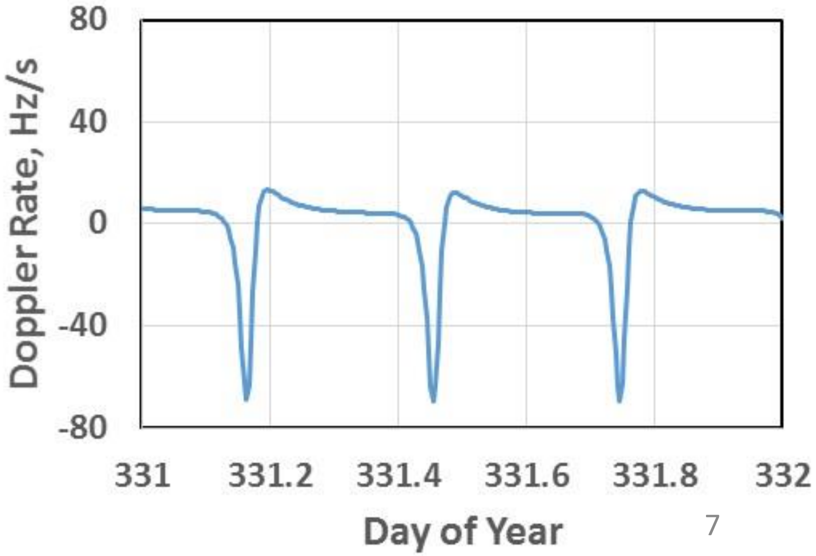
Table 1			
Relative Doppler Shifts between Spacecraft at Mars			
X-band			
Spacecraft Pair	Average (kHz)	Min (kHz)	Max (kHz)
ODY-MRO	-0.003	-90.6	89.2
ODY-MAVEN	-0.026	-158.0	108.8
ODY-MOM	-0.306	-88.6	154.1
ODY-MEX	0.025	-115.3	153.1
MRO-MAVEN	-0.023	-90.1	66.5
MRO-MOM	-0.303	-28.7	84.0
MRO-MEX	0.028	-73.4	102.3
MAVEN-MOM	-0.280	-54.8	163.2
MAVEN-MEX	0.051	-85.0	163.0
MOM-MEX	0.331	-135.9	94.3

MUPA – Geometry, cont'd

- Examined case of 5 the five spacecraft for a one day period: November 26, 2016 (day 331) relative to 7.15 GHz (bottom left)
- We consider MEX where Doppler offset is ~ ±70 kHz (top right) and Doppler rate magnitude is high as 70 Hz/s (bottom right)
  - We have considered cases with Doppler offsets of order 100 kHz and Doppler rates up to 70 Hz/s in our analysis







Signal Acquisition Approaches

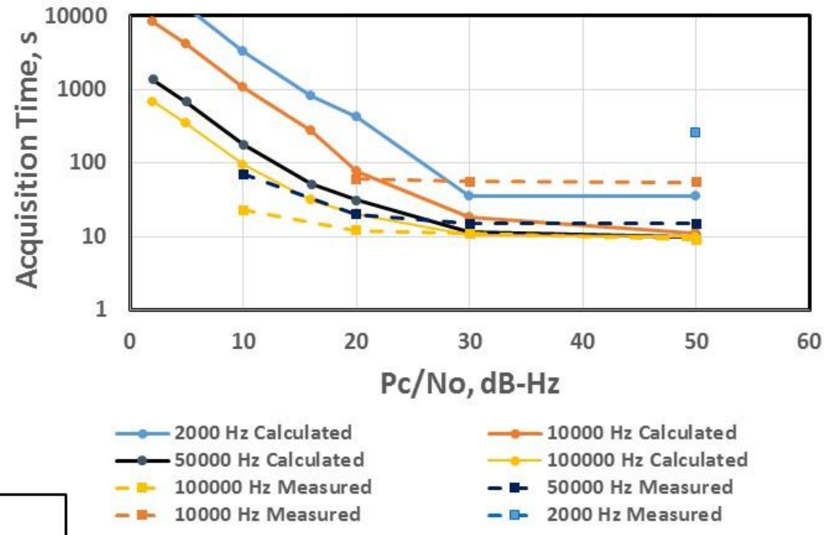
- FFT Signal Search
- Step-and-Sweep Signal Search
- On-board Tuning of SDR

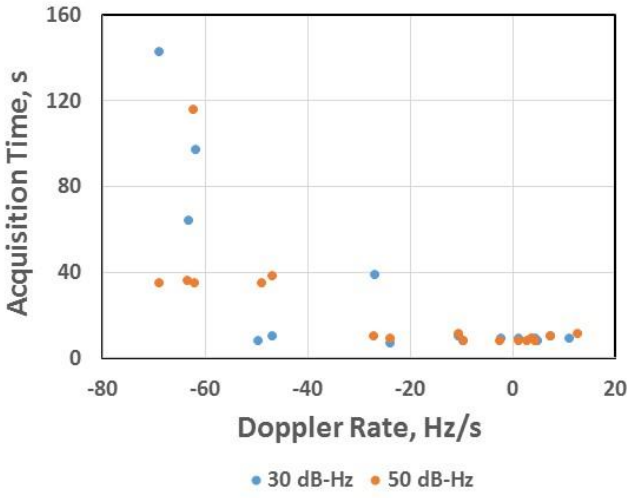
FFT Signal Acquisition

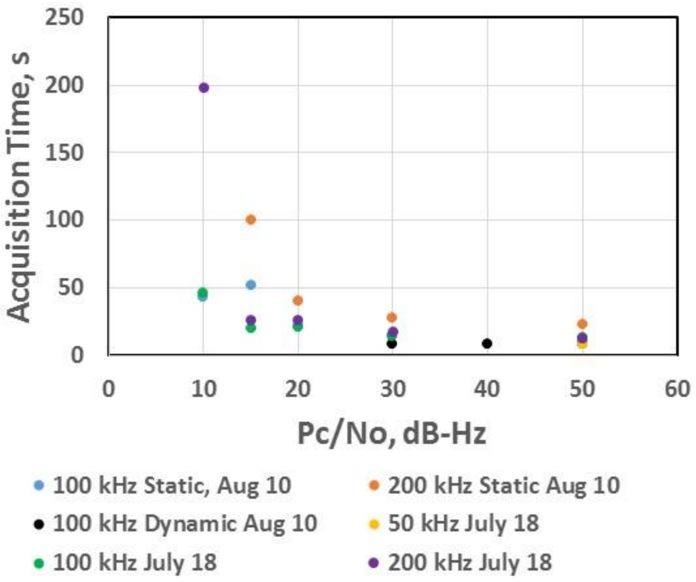
- The FFT signal search algorithm has been utilized by several entities when a large frequency uncertainty window is required to be searched
- When there are high (uncompensated) dynamic conditions and relatively weak signal levels, the FFT algorithm may be plagued with issues of smearing and thus have difficulties achieving stable lock
  - Such algorithms are used for signal acquisition scenarios involving LEOs involving high dynamics and low signal strengths
  - The use of such techniques may be considered in future studies but are beyond the scope of this paper if one decides to go the FFT route.
  - We have focused on “carrier-only” acquisition in this study

FFT Signal Acquisition (cont'd)

- FFT algorithm was explored by making use of the DSN ground system receiver using both calculated values (solid curves) and testbed measurements (dashed curves) as shown in plot to right
  - Case of 100 kHz frequency offset with measurements from June 27, 2017
- DSN FFT algorithm has limitations due to receiver constraints (relatively low acquisition bandwidth)
- For large frequency uncertainty regions, it is recommended to use large FFT bandwidths over a large frequency search range
- Plots below display signal acquisition times as a function of Doppler rate (left) and received signal strength (right) from 2017 testing







Step-and-Sweep Signal Acquisition

- Another technique makes use of the step-and-sweep algorithm, where frequency uncertainty range is partitioned into successive discrete overlapping search bands (see below)
- The NCO is successively tuned to the middle of each band, and the radio performs a signal search within each carrier loop acquisition bandwidth, from one end of the frequency search bandwidth to the other end
- If insufficient energy is encountered in one band, the algorithm steps into the next search band, with some overlap
- Once a signal of sufficient energy is found, the algorithm may continue to search adjacent bands until the band with maximum signal amplitude is identified
- The NCO is then tuned to this frequency and the radio attempts lock
- Example below depicts one full cycle of carrier signal search steps for a search range of 32 kHz

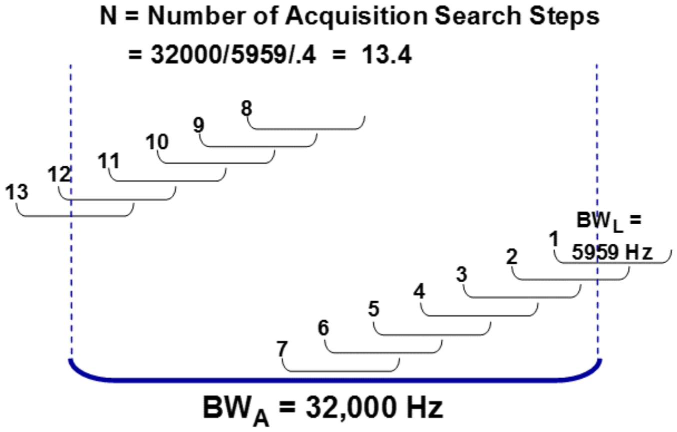
BW_A = Acquisition Search Bandwidth

BW_L = Acquisition Carrier Loop Bandwidth

Freq Search Step Size = 0.4 x BW_L

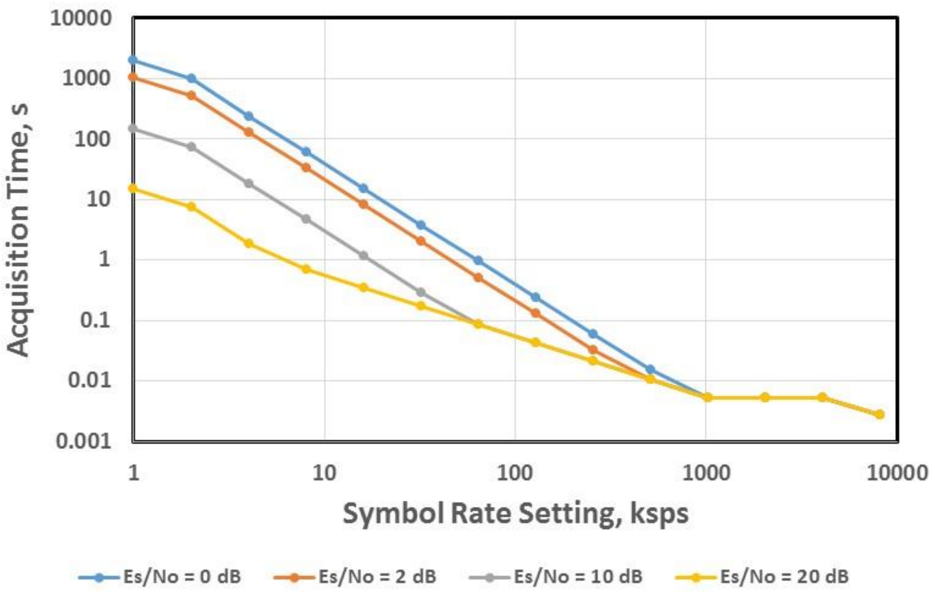
N = Number of Acquisition Search Steps

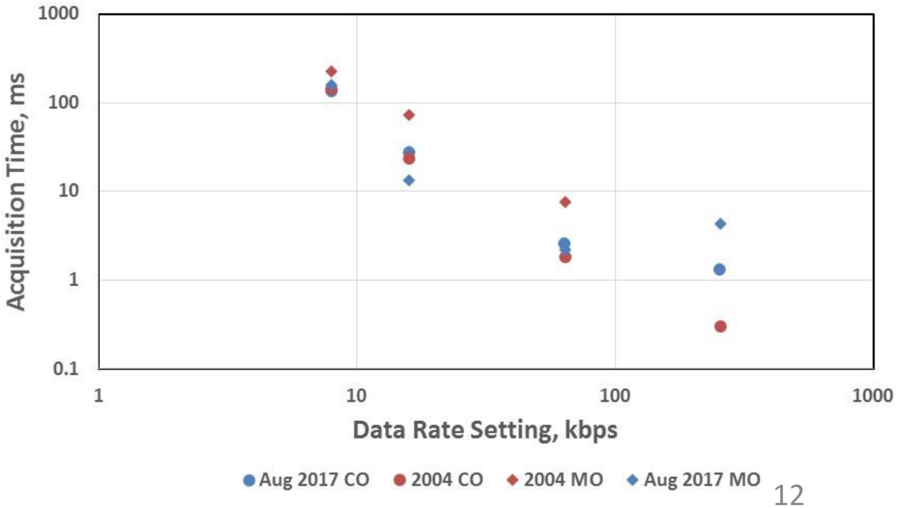
$= \lfloor BW_A / (0.4 BW_L) \rfloor$



Step-and-Sweep Signal Acquisition, cont’d

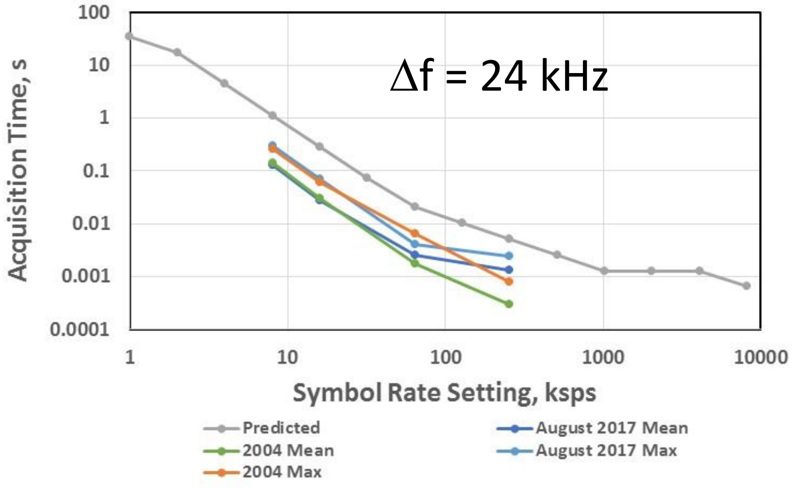
- Electra radio provides communications and navigation services for Mars mission proximity links
  - Used in proximity links between landed assets and orbiters
  - Employs digital approach where the incoming waveform is downconverted to baseband and I,Q components are digitally generated, sampled and processed
  - Acquisition/tracking loop is 2nd order PLL, loop BW = 10 Hz to 10 kHz
- Figure (top) – Predicted acquisition times
  - Predicted carrier acquisition times for given symbol rate settings and Es/No settings for a frequency search window of 100 kHz
- Figure (bottom) –
  - Carrier-only (CO) acquisition times for tests on Aug. 29, 2017 (blue circles) and corresponding results from 2004 tests (red circles)
  - Carrier acquisition times with modulation on (MO) (blue diamonds) and corresponding results from 2004 tests (red diamonds)
  - These tests involved an Es/No setting of 10 dB resulting in different acquisition times for frequency offsets of up to 24000 Hz

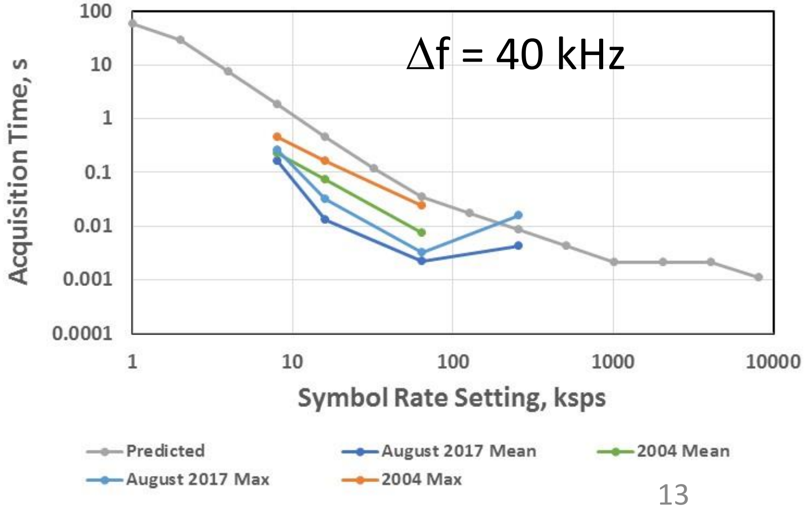




Step-and-Sweep Signal Acquisition, cont'd

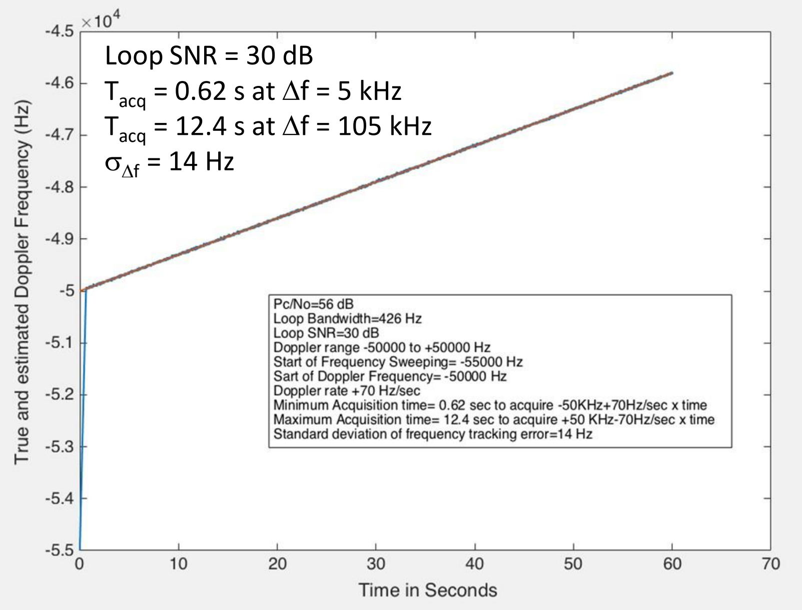
- Figures depict predicted acquisition times using algorithm (gray) for frequency offsets of 24 kHz (top) and 40 kHz (bottom)
- Also plotted are mean and maximum acquisition times from tests (color)
- Measured acquisition times (colored) are basically quicker than predicted times (gray)
  - Predicts assume entire offset region is searched
  - Test results depend on selection of center frequency relative in search region

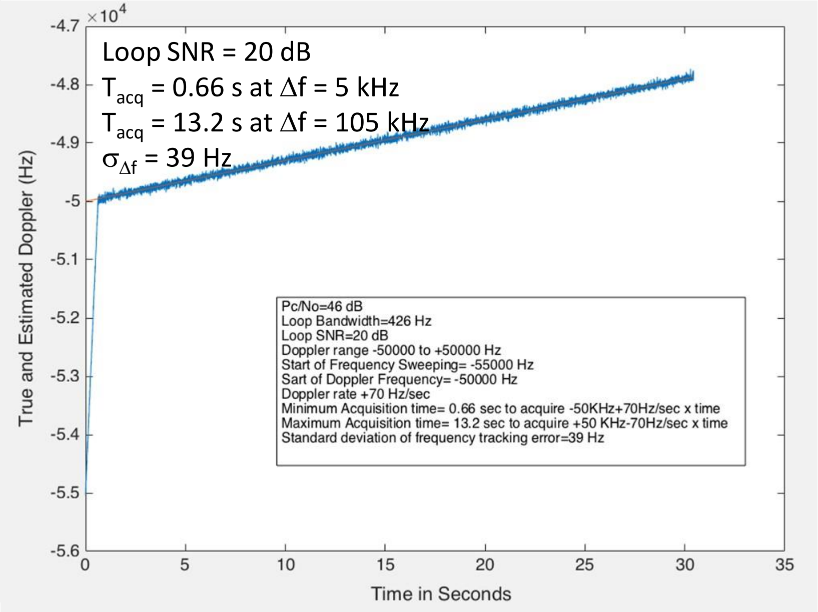


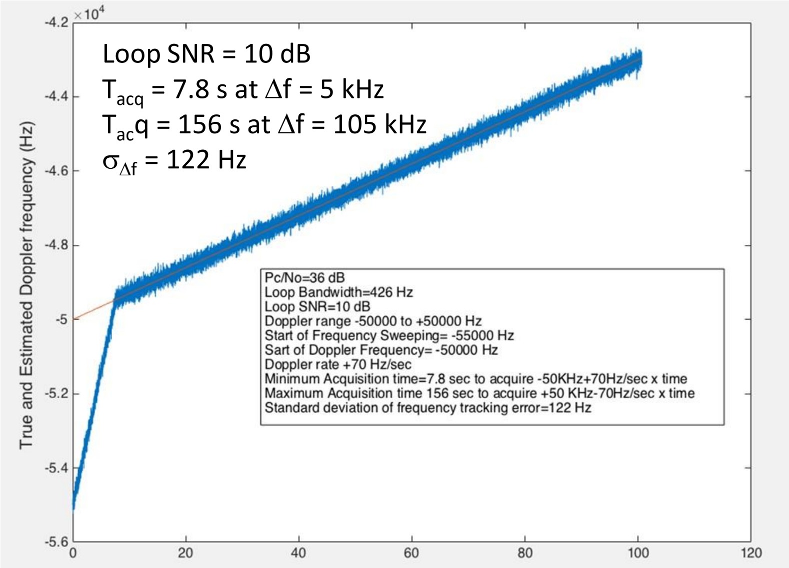


Step-and-Sweep Signal Acquisition, cont'd

- A non-conventional step-and-sweep approach was explored using a simulation tool (SIMULINK), that differs from Electra
  - This approach involves more versatility in varying step-sizes, thresholds, and frequency search directions
- SIMULINK was configured to evaluate how a tuned PLL would respond to a 70 Hz/s Doppler rate at different loop SNRs (30, 20 and 10 dB) and frequency offsets
  - Lock occurred < 14 s for 20 dB and 30 dB values of loop SNR with a 105 kHz frequency offset (left and center plots)
  - The 10 dB case (right plot) required increasing integration time for lock detector and decreasing the frequency step size in the sweeping algorithm
  - These results consistent with Electra test results using similar parameter values (e.g., carrier loop BW, SNRs, etc.)
- SIMULINK runs courtesy of Dariush Divsalar, Jet Propulsion Laboratory, April 26, 2018
  - Reference: K. Cheung, D. Divsalar, "Simultaneous Two-Way Doppler and Ranging for Multiple Spacecraft at Mars: Flight Radio Tracking System Design and Performance Simulations," SpaceOps 2018







Step-and-Sweep Signal Acquisition, cont’d

- Recent 2017 Electra tests produce similar results to 2004 tests (few ms to few sec acquisition times)
- Examined Electra step-and-sweep carrier acquisition/lock times over multiple runs for several cases of loop SNR and frequency offsets for static signals (zero Doppler rate)
    - Lock easy occurs within 50 ms for all cases of loop SNR
    - Larger frequency offsets (e.g. 99 kHz) produce results in higher acquisition times over smaller offsets (e.g., 49 kHz)
- Examined SIMULINK for high Doppler rate and different loop SNRs
    - Resulted in ~ 14 s acquisition times at high loop SNRs and ~156 s for lower loop SNR for 105 kHz offset
    - Produced longer acquisition times due to smaller loop BW and high dynamics (~70 Hz/s) than above Electra static results
    - Results consistent with Electra 2004 test results using similar parameter values (e.g., carrier loop BW, SNRs, etc.)

On-Board Tuning

- On board tuning can be used to allow for quick signal acquisition when dealing with large frequency uncertainty regions using a single uplink to multiple spacecraft
- This can be accomplished by periodically uplinking appropriate trajectory/ephemeris information to the spacecraft along with knowledge of the location of the uplink station
- The on-board software can either
  - Perform the appropriate estimation process from on-board trajectory information (state vectors) to yield expected Doppler frequency as a function of time
  - Or make use of an uplinked look-up table of expected Doppler frequencies for given passes
- Near the start of a tracking pass, the flight software will send an estimate of the frequency to the digital processing firmware in the radio to steer the NCO close to the expected uplink frequency where it can then perform acquisition
- For cases where there are short periods of time between passes, the flight software can be programmed to send instructions to the firmware to change filter coefficients with a shorter time constant

On-Board Tuning, cont'd

- This technique was explored by Johns Hopkins University Applied Physics Lab (JHU/APL) and is planned for use in a future proximity link involving the Frontier radio
- The Parker Solar Probe and Europa missions do not plan to make use of any non-standard acquisition strategies for direct-to-earth communications as they will rely on Doppler-compensated uplinks
  - However, the Europa Clipper mission does plan to make use of non-standard digital signal detection techniques for the relay between the Clipper spacecraft and the potential lander
  - A technique will be employed whereby the receiver accepts a Doppler prediction frequency to shift the carrier acquisition loop by a fixed offset in frequency to aid in acquisition and lock
- Some signal acquisition/lock testing was performed for the Frontier radio to test robustness and acquisition of the symbol tracking loop in low SNR conditions with different command rates and Doppler offset conditions
  - Low data rate (7.8125 bps) - Acquisition times varied from ~ 26 s for a large Doppler offset to ~ 10 s for a small Doppler offset
  - High data rate (2 Mbps) – Acquisition times were much smaller (~ 40 ms)
    - Reference: Kufahl, K., Adams, N., and Kirschner, W., "Data Acquisition Performance for Deep Space Communications in Solar Probe Plus Frontier Radio", 2016 IEEE Aerosp. Conf., Big Sky, MT, 2016

Trades

- On-board tuning
  - Initial indications are that available SDRs can easily accommodate on-board frequency tuning assuming that trajectory information is available on spacecraft along with ground station support information
  - Appropriate software needs to be programmed on the spacecraft computer to allow periodic tuning of the NCO in the firmware
- The step-and-sweep algorithm such as used by the Electra radio has been successful
  - This algorithm can be easily implemented on several current SDR designs used for deep-space communications
    - Provision is available on some radios allowing NCO tuning from the spacecraft computer to the radio firmware, with minimal refinement
  - In this case, the algorithm on-board the spacecraft computer would likely make use of a frequency uncertainty range and a search algorithm involving various step parameters (bandwidths, dwell times, etc.)
- A usable FFT search algorithm would require additional modifications to firmware and judicious exchange of information, such as commanding and processing between radio firmware and flight computer
  - Provision needs to be made to allow for movement and processing of large arrays of IQ samples to discern presence of signals
  - FFT searches are routinely performed by GPS receivers, and may be beneficial for future designs of deep-space radio firmware and on-board computer software algorithms
- Signal acquisition performance is dependent upon radio capabilities such as loop update time (clock speed), bandwidth settings as well as receiver sensitivity
- Future studies would include a quantitative comparison of lock times or probability of lock based on the exercise of the various signal acquisition schemes for a given radio

Future Studies

- Several different radios are being explored to investigate different signal acquisition algorithms for proposed future tests
  - Some potential testbeds/radios that have been considered include Electra, Iris, CoNNeCT, UST and ML-605
  - We would use these testbeds (or available engineering models) to develop and exercise signal search/acquisition algorithms expected for high Doppler offset and rate operations

Conclusions

- Three signal acquisition schemes explored
- On-board tuning appears to be preferable
  - Requires trajectory information to be uplinked to each member spacecraft along with ground station information (location, uplink frequency, etc.)
  - Requires some on-board processing SW
    - Spacecraft computer can perform the necessary processing of the trajectory file to obtain a set of tuning frequencies (or a look-up table of frequencies for each tracking pass can be utilized)
    - On-board computer sends estimated frequencies to firmware allowing tuning of digital PLL (NCO)
- In lieu of on-board tuning, a step-and-sweep algorithm can easily be implemented
  - Can be performed in spacecraft computer, periodically sending sequences of tuning frequencies to firmware
  - Frequency uncertainty region as well as step-size could be programmed into software
  - Between passes, computer can send filter coefficients to firmware to “zero” or reset frequency
- FFT signal search more problematic but feasible
  - Manipulation of arrays of IQ numbers, more exchange of information between computer and firmware
  - Requires additional programming, testing, etc.

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